Remote defect imaging for plate-like structures based on the scanning laser source technique

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Remote Defect Imaging for Plate-like Structures Based on the Scanning Laser Source Technique

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Abstract. In defect imaging with a scanning laser source technique, the use of a fixed receiver realizes stable measurements of flexural waves generated by laser at multiple rastering points. This study discussed the defect imaging by remote measurements using a laser Doppler vibrometer as a receiver. Narrow-band burst waves were generated by modulating laser pulse trains of a fiber laser to enhance signal to noise ratio in frequency domain. Averaging three images obtained at three different frequencies suppressed spurious distributions due to resonance. The experimental system equipped with these newly-devised means enabled us to visualize defects and adhesive objects in plate-like structures such as a plate with complex geometries and a branch pipe.

INTRODUCTION

Laser ultrasonics is widely used as a means of non-contact material evaluation [1-4]. Generally, a laser pulse irradiated onto the surface of a material generates ultrasonic pulse and the pulse wave is detected on the material surface using laser interferrometory. The non-contact measurements realize high temperature inspection of weld lines and full inspection of products at the production line. Moreover, C scan images can also be obtained with the non-contact technique.

However, considering the inspection for such pipes in plants and outdoor structures, various problems remain in the practical use. For example, when inspected objects have curved or rough surfaces such as pipes and concrete structures, reflected and scattered light from such surfaces often is received unstably, which disturbs C scan measurements.

Therefore, the authors of the current paper have developed defect imaging using a scanning laser source (SLS) technique, in which stable non-contact measurements are achieved because only a laser for elastic wave source is rastered and a laser for detecting vibration is fixed at a certain point [5-11]. Plotting the value of amplitude or frequency spectrum peaks for laser source positions gives an image of defects in the plate-like structure. This imaging technique is based on a very simple principle that flexural vibration energy varies with bending stiffness at the laser source. The SLS measurements are easily implemented without precise adjustment of optical parts. The authors have already published fast imaging and defect imaging for curved plates using the characteristics.

This paper shows the results of imaging of complex plate-like structures at remote positions aiming at the realization of imaging inspection for large structures from remote measurements.

DEFECT IMAGING BY SLS IN LOW FREQUENCY RANGE

When a laser pulse is irradiated on solid media, elastic wave is generated by thermo-elastic effect or ablation [1-4]. Now, considering very low frequency range (e.g., 5 kHz - 50 kHz) compared with the range used in general ultrasonic inspections, the elastic waves act as Lamb waves propagating along the plate surface. In metallic plates of the thickness of a few mm, flexural vibration (A0 mode) is generated in such a low frequency range.

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Figure 1 shows variations of flexural waves generated by laser in a plate with a gently-sloping wall-thinning. When a laser source is located at an intact range, flexural waves generated in the plate are small and the signals detected at a certain point of the plate are also small. While for laser incidence on the defect region, flexural waves are generated larger and the signals detected at the same point also become larger. This energy variation is caused by the characteristic that flexural wave energy varies with a plate thickness at the laser source. Authors experimentally verified that images of defects in a plate can be obtained by rastering a laser source over the plate surface [5].

It was also theoretically and experimentally verified that flexural wave energy generates larger for a laser source in the vicinity of a notch type defect in a plate [7, 8]. Authors proved using a semi-analytical finite element method that the energy enhancement in the vicinity of the notch type defect is caused by the interactions of evanescent modes generated by the laser emission and reflection [7]. The evanescent modes decrease exponentially with the distance from the sources (in this case, the laser source and the notch) and the dominant distance is significantly short compared with the wavelength of the flexural propagating wave. Therefore, the energy enhancement due to the interaction of the evanescent modes occurs only when the laser source is located very close to the notch type defect. Specifically, when a laser source is rastered over a plate surface and flexural waves generated from the laser source are detected for all rastering points, the distribution of the signal amplitude corresponds to the defect image. Because the resolution of the image becomes much smaller than wavelength of the flexural wave (A0 mode of Lamb wave), we can use low frequency range of kHz order that has not been utilized in ultrasonic inspection, which enables us to use a wide variety of vibration measurement means.

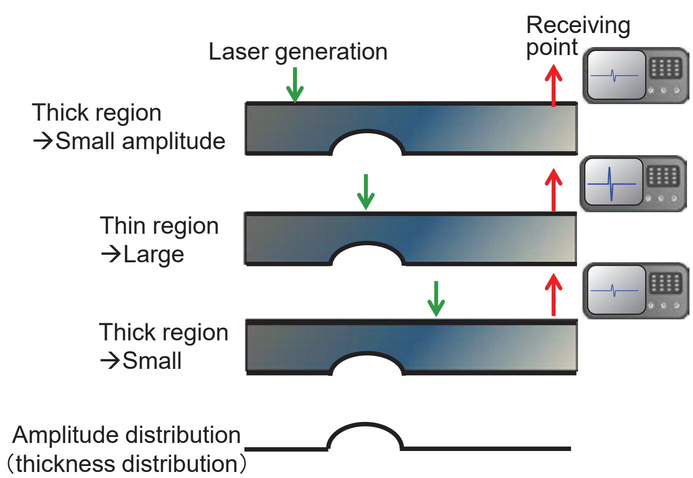


FIGURE 1. Principle of energy enhancement

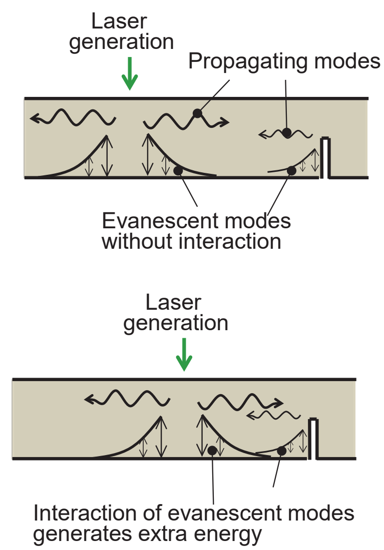


FIGURE 2. Evanescent modes around a notch type defect and a laser source

EXPERIMENTAL SET-UP

Generally in laser ultrasonics, a giant laser pulse is emitted from Nd: YAG laser or pulsed CO_2 laser and elastic wave in MHz range is generated by the laser pulse for material evaluation. Since the defect imaging technique in this study uses low frequency range, a fiber laser was adopted for generating elastic waves [9-11]. In a fiber laser, laser pulses can be generated at high repetition rate and the output is controlled by external modulation signals. Rectangular burst signals at 24 kHz, 30 kHz, and 36 kHz are used in this study for modulating laser output and generating narrowband burst wave at the frequencies in plate-like structures. Because generated waveforms are controlled by the external modulation signals, defect images can be obtained at different frequencies. A chirp wave and other arbitrary waveforms can also be used for the imaging. Moreover, burst waves with long duration enhance signal to noise ratio (SNR) in frequency domain even using a low peak power laser. Improvement of SNR requires use of a laser Doppler vibrometer as a receiving devise that is generally less sensitive than contact transducers. In addition, the low maximum power laser is effective and also avoids damage of the material surface.

Figure 3 is a schematic figure of output laser pulses and modulation signals used in this study. Laser pulses were output at the repetition rate of 580 kHz modulated by the rectangular signals of 24 kHz, 30 kHz, and 36 kHz. Elastic waves containing the three frequency components were generated at each source point by the use of the modulation signals connecting these three rectangular signals in a series, as shown at the bottom of Fig. 3. After receiving the waveforms, Fourier spectra of them were taken and peaks at the three frequency bands were plotted on the 2D map, and then these images were averaged. Reference [10] described how this technique, called Frequency Image Averaging (FIA), works well to reduce spurious images caused by resonance. Modulation signals used in this study were set to 1.5 ms duration for each frequency component.

Figure 4 is the experimental set-up used in this study. Galvano mirror scanners moved laser beam to the rastering points and the flexural vibration generated for each laser irradiation point were detected by a laser Doppler vibrometer. The detected signals were transferred to a personal computer after being amplified at 60 dB and digitized. Then, fast Fourier transform was performed and the FFT peaks were plotted in a two dimensional map. Although the distance between the experimental system and the specimens were set to about 6.0 m due to the limitation of the laboratory space, serious problems cannot be found in longer-distance operation.

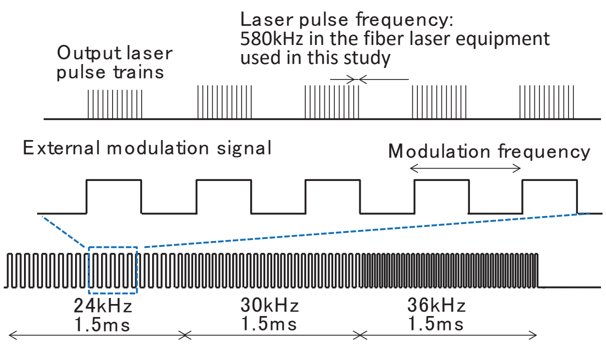


FIGURE 3. Modulation signal and output laser pulse trains

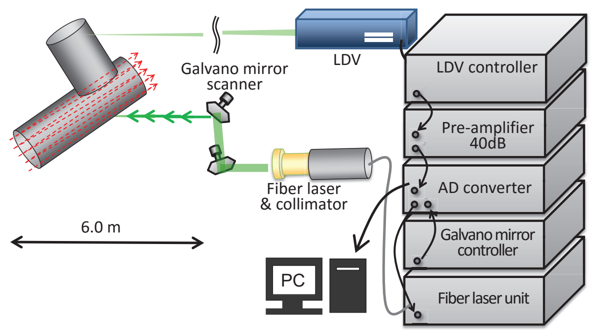
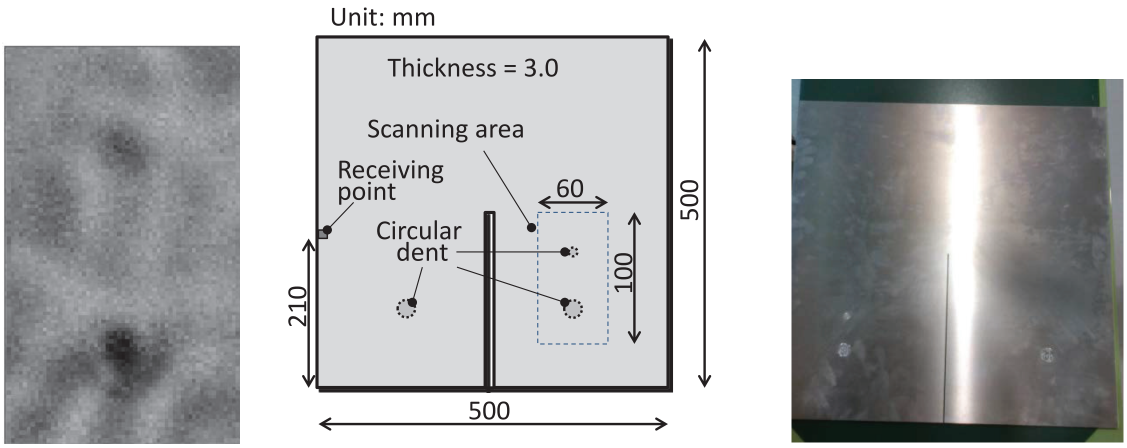


FIGURE 4. Experimental set-up

CASE STUDIES OF REMOTE DEFECT IMAGING

Using the experimental system, imaging experiments were implemented for various specimens. As discussed in Hayashi [8], this imaging technique can be applied to a plate-like structure with complex geometries. Therefore, as a typical examples of complex structures, an aluminum alloy plate with a through notch, a T-shaped steel plate, and a branch pipe are considered below and images of defects and adhesives are obtained by remote measurements.

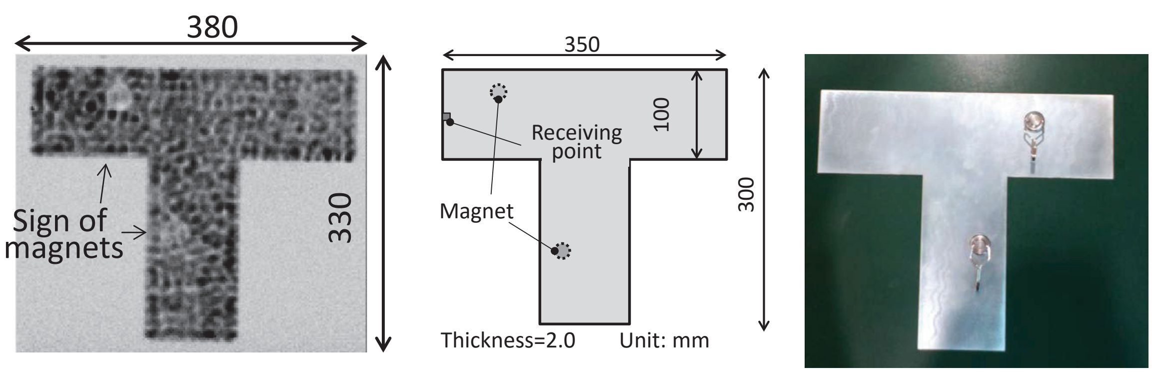
Figure 5 (a) is an image obtained for the artificial circular dents in an aluminum alloy plate as shown in Fig. 5 (b) and (c). The specimen was 3.0 mm thick, having two circular dents of 1.5 mm in depth and 10 mm and 20 mm in diameter on the back surface as artificial defects. The laser for generating elastic wave was rastered over the area of 60 mm ×100 mm behind the two dents (a dashed square in Fig. 5 (b)) at 1.0 mm increment. The elastic waves were detected at the point shown in the figure. Between the elastic wave source by the laser and the detection point, a through notch was made to block the direct transmission wave in order to confirm the validities of the imaging technique even for such complex structures [8]. The dark spots appear at the appropriate positions, showing that the defect imaging is working well.



(a) (b) (c)

FIGURE 5. Circular dent case

Next, an image was obtained for a T-shaped steel plate attached with two magnets as shown in Fig. 6 (a) by the same imaging process. Figures 6 (b) and (c) are dimensions of the steel plate and a photo taken from the back surface. Laser beam for generating elastic wave was rastered at 2 mm increments over the area of 380 mm × 330 mm covering full range of the plate. Intensity becomes small at the area that the magnets adhered to, which is caused by the fact that energy of flexural vibration becomes small due to the increase of apparent bending stiffness at the magnet areas. The other patterns were caused by mixture of multiple resonance patterns. This result shows that the imaging technique has a potential to detect scales in a pipe.



(a) (b) (c)

FIGURE 6. A T-shaped steel plate attached with magnets

The last case study shows a branch pipe with an inner wall-thinning (Fig. 7 (a)). Two aluminum pipes of 100 mm diameter and 3.0 mm thickness were welded as shown in Fig. 7 (b), and a wall-thinning of the maximum depth of 1.5 mm was made on the inner surface of the dashed rectangular line. Laser was rastered over the range of 550 mm × 370 mm at 2 mm increment, and flexural vibrations were detected at the upper edge of the branch pipe. A large intensity region can be obtained at the position of the wall-thinning, which indicates that the imaging technique performed appropriately. The striped patterns close to the receiving position also appeared clearly, which indicates resonance patterns of circumferentially propagating waves.

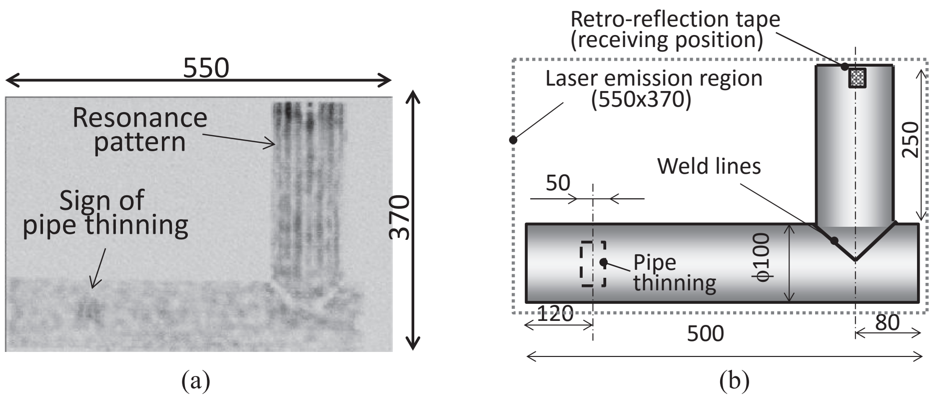


FIGURE 7. Branch pipe

These results show that remote defect imaging was possible for such plate-like structures with complex geometries. However, we may need to use a'priori information such as possible defect shape and locations for more accurate defect detection because resonance patterns were sometimes largely superposed with defect images.

CONCLUSIONS

To realize defect imaging of remote structures, an experimental system equipped with a laser Doppler vibrometer as a receiver was constructed and defect imaging experiments were implemented for plate like structures at 6 m away.

Signatures of dent, adhesives, and a wall-thinning were appropriately visualized for an aluminum plate with circular dents, a T-shaped steel plate with magnets on the back surface, and a branch pipe with an artificial wall-thinning. However, it should be noted that resonance patterns were observed at the same time.

ACKNOWLEDGMENTS

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REFERENCES

1. C. B. Scruby and L. E. Drain, *Laser Ultrasonics*, Techniques and Applications, CRC Press, 1990, ISBN 0750300507.
2. T. Sanderson, C. Ume, and J. Jarzynski, "A Comparison of Q-switched and intensity modulated laser pulses for ultrasonic NDT," *J. Nondestruct. Eval.* **17**, 199–208 (1998).
3. J. D. Achenbach, "Laser excitation of surface wave motion," *J. Mech. Phys. Solids* **51**, 1885–1902 (2003).
4. M. Ochiai, T. Miura, T. Onodera and S. Yamamoto, "Laser-ultrasonic study of micro crack sizing and its application to nuclear reactor internals," *Hozengaku*, **4,** 41-46 (2006).
5. T. Hayashi, M. Murase, and M.N. Salim, "Rapid thickness measurements using guided waves from a scanning laser source," *J. Acoust. Soc. Am.* **126**, 1101–1106 (2009).
6. T. Hayashi, M. Murase, and T. Kitayama, "Frequency dependence of images in scanning laser source technique for a plate," *Ultrasonics* **52**, 636–642 (2012).
7. T. Hayashi and M. Fukuyama, "Vibration energy analysis of a plate for defect imaging with a scanning laser source technique," *J. Acoust. Soc. Am.* **140**, 2427–2436 (2016).
8. T. Hayashi, "Imaging defects in a plate with complex geometries," *Appl. Phys. Lett.* **108**, 081901 (2016).
9. T. Hayashi and K. Ishihara, "Generation of narrowband elastic waves with a fiber laser and its application to the imaging of defects in a plate," *Ultrasonics.* **77**, 47-53 (2017).
10. T. Hayashi, "High-speed non-contact defect imaging for a plate-like structure," *NDT E Int.* **85**, 53–62 (2017).
11. T. Hayashi, "Non-contact imaging of pipe thinning using elastic guided waves generated and detected by lasers, " *Int. J. Press. Vessel. Pip.* **153**, 26–31 (2017).